RESEARCH ARTICLE

Numerical Simulation of Novel Hybrid Solid Desiccant Bed for Drying

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ABSTRACT: In this paper, a novel design of hybrid stationary packed solid desiccant bed is proposed and numerical simulation of the performance for drying of gases is presented. The pro-posed hybrid packed beds is consists of a mixture of solid desiccants of different types having both fixed and varying particle diameter distribution along the vertical axis direction. Generally in the beds of this type, the drying time taken for the bed saturation is hugely related to the input condition of the gases. Also, the adsorption isotherm curves of different desiccant types have a strong effect on the exit conditions of the gases dehumidified/dried using these beds. In order to simulate the transport phenomena associated with the hybrid packed solid desiccant bed application, an in-house CFD code using finite volume method is developed. This CFD code has the capability to model the simultaneous heat conduction and moisture diffusion taking place in the bed during the gas transport. The numerical results of the base model design are validated against the experimental data available in the literature. The estimated exit temperature and moisture content of the gas are in good agreement with the literature data. Further, the validated model is used to simulate for several other novel packed bed designs, the coupled heat and mass transfer in adsorption and desorption phases under wide operating conditions. The results of interest includes the assessment of improvement in performance of dehumidifying/drying of gases in terms of pressure dew point, relative humidity at exit and the prediction of the desorption phenomena for the regeneration of the beds for next cycle of operation. Finally, the paper summarizes the benefits of this novel hybrid design and highlights the potential design cost benefit.

KEYWORDS: Packed beds, Hybrid solid desiccants, drying of gases, Numerical simulation, Finite volume methods.

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INTRODUCTION

The stationary hybrid fixed desiccant bed is filled with solid desiccant particles as shown in Figure 1. The moist air is supplied to the bed and dry hot air exits at the outlet during the adsorption process [1]. During the adsorption process water-vapor molecules are transferred from the bulk air-flow to the desiccant surface due to vapour pressure difference, and the direction of mass transfer is inversed during the desorption process and the desiccant bed gets regenerated. As the moisture vapour pressure on the surface of the desiccant particle is highly influenced by the desiccant temperature and the moisture content on the desiccant, the heat of adsorption is dependent on the mass transfer rate, which is mainly depended by the moisture vapour pressure on the desiccant surface. Hence, this issue of adsorption and desorption in the hybrid fixed desiccant bed must be treated as a coupled transient heat and mass transfer phenomena, which are numerically simulated [2] and experimental measure of the performance of the beds [3 & 4]. This adsorption and desorption phenomena is analyzed for rotary desiccant wheel application as well [5-7].

A novel hybrid packed beds [8] are proposed to improve the adsorption and desorption phenomena during the drying application. The hybrid desiccant beds [9-12] show the capability to achieve a further low dew point temperature for the drying applications.

The concept of novel hybrid desiccant packed bed proposed along with conventional Silica gel (SG) and Molecular Sieves (MS) beds for performance comparison purpose is shown in Figure 1.

- SG desiccant bed
- MS desiccant bed
- Hybrid bed of 1/2 SG and 1/2 MS desiccant

In this hybrid desiccant bed, the half of the bed volume at the bottom is filled with SG desiccant and the remaining half of the portion at the top of the tower is filled with MS desiccant (Zeolites). By this novel concept, the higher adsorption capacity of the silicagel desiccant is utilized to adsorb the maxi-mum moisture at the entry portion of the tower and then the remaining moisture content in the air is effectively adsorbed using molecular sieves desiccant, as molecular desiccant is having much higher adsorption capacity than silicagel at lower relative humidity

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conditions. This is a unique advantage of this hybrid packed bed as compared to the conventional beds of entirely using either silicagel or molecular sieves.

The objective of this paper is to present the novel design of hybrid stationary packed solid desiccant bed to achieve superior DPT while retaining the same size and volume for the conventional SG and MS bed for comparison purpose. Also the CFD code is to simulate the performance of the packed bed and validating the results with experimental results from literature and then to present to the potential benefit of using hybrid bed in the place of conventional packed beds.

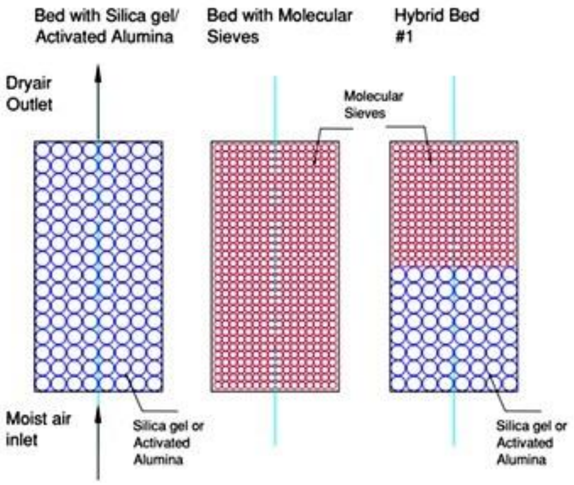
Bed with Silica gel/ Activated Alumina
Bed with Molecular Sieves
Hybrid Bed #1
Dryair Outlet
Molecular Sieves
Moist air inlet
Silica gel or Activated Alumina
Silica gel or Activated Alumina

Fig. 1 Hybrid stationary packed solid desiccant bed

Governing equations

The governing equations in the form of partial differential equations are derived [3, 4] based on the conservation of mass/moisture and conservation of energy/heat in the air and in the desiccant.

The mass/moisture conservation of the air in the solid desiccant packed bed is given by partial differential equation as below:

$$\frac{\partial W}{\partial t}=\frac{k_m a}{(1-\varepsilon)\rho_s}(\omega_a-\omega_s) \tag{1}$$

Mass/moisture conservation in desiccant for the solid desiccant packed bed is given by partial differential equation as below:

$$\frac{\partial \omega_a}{\partial t}=-\frac{G_a}{\varepsilon\rho_a}\frac{\partial \omega_a}{\partial y}+\frac{k_m a}{\varepsilon\rho_a}(\omega_s-\omega_a) \tag{2}$$

Heat energy conservation in the solid desiccant packed bed air is given by partial differential equation as below:

$$\frac{\partial \theta_a}{\partial t}=\frac{G_a}{\rho_a\varepsilon}\frac{\partial \theta_a}{\partial y}+\frac{k_h a}{\rho_a C_a\varepsilon}(\theta_a-\theta_s)+\frac{C_v k_m a}{C_a\rho_a\varepsilon}(\omega_a-\omega_s)(\theta_a-\theta_s) \tag{3}$$

Heat energy conservation in the desiccant for the solid desiccant packed bed is given by partial differential equation as below:

$$\frac{\partial \theta_s}{\partial t}=\frac{\lambda_{eff}}{(1-\varepsilon)\rho_s c_s}\frac{\partial^2 \theta_s}{\partial y^2}+\frac{\Phi}{c_s}\frac{k_m a}{(1-\varepsilon)\rho_s}(\omega_a-\omega_s)+\frac{k_h a}{(1-\varepsilon)\rho_s c_s}(\theta_a-\theta_s) \tag{4}$$

The initial, periodic and boundary conditions are referred from literature [2] to compare the numerical results [2,3].

Numerical modeling and methodology of solving governing equations

The governing partial differential equations are discretized by using finite volume method under implicit scheme to get set of linear algebraic equations and these linear equations are solved with the boundary conditions and input conditions using the CFD code developed in FORTRAN 95, as shown by the flow diagram in Figure 2.

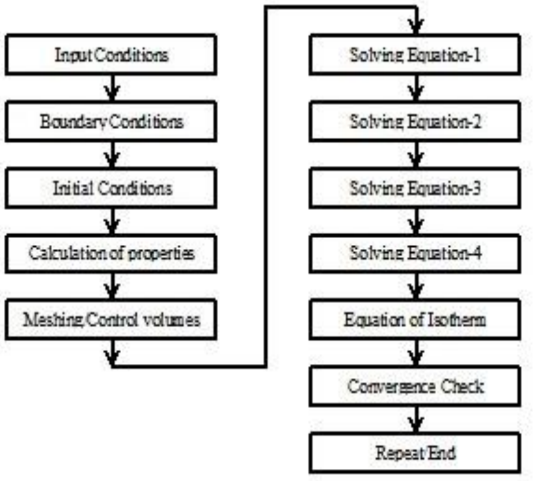

Fig. 2 Modeling and methodology of solving governing equations

Validation

The simulated results of present model are compared with numerical results [1 & 2] and experimental [3] results from the literature. The parameters of packed bed are shown in Table-1.

The numerical model shows a finer agreement with experimental data for the exit air temperature and moisture content of process air during adsorption, as shown in Figure 3.

RESULTS AND DISCUSSION

The moisture content and air temperature for the bed sections across the length for various inlet moisture content from 5-20 g/kg are predicted by numerical model, as shown in Figure 4. It is evident that the process air temperature is directly depending on the moisture content removal, which is in turn related to the inlet moisture content of process air.

Table 1. Parameters of the packed beds

Diameter of the packed desiccant beds	130 mm
Diameter of the desiccant particles	3.88 mm
Height of the desiccant packed	77.5 mm
Desiccant type used	Molecular Sieves(MS) , Silicagel (SG)
Temperature of Process air inlet	23.3 ^{0}C
Moisture content of Process air inlet	18 g/kg of dry air
Relative humidity of Process air inlet	100%
Porosity of the desiccants	0.4
Ratio of air flow passage area to bulk area	81.6%
Maximum adsorption capacity,	0.35 for SG, 0.25 for MS
Operating time of the packed bed, t	1800 sec

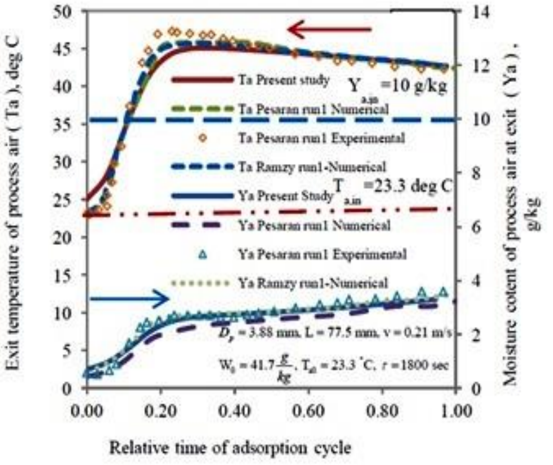

Fig. 3 Validation of numerical results with experimental results

The corresponding moisture removal capacity (MRC) and relative moisture removal efficiency (RMRE) are plotted for the bed sections across the length for various inlet moisture content from 5- 20 g/kg is shown in Figure 5. It is seen that MRC is directly depending on the inlet moisture content of process air, however, the RMRE is inversely proposal to inlet moisture content.

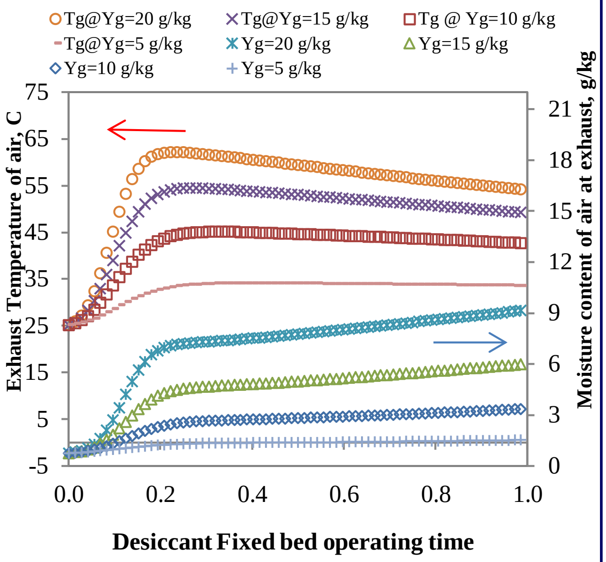

Fig. 4.Calculation of exit temperature for different inlet moisture and temperature

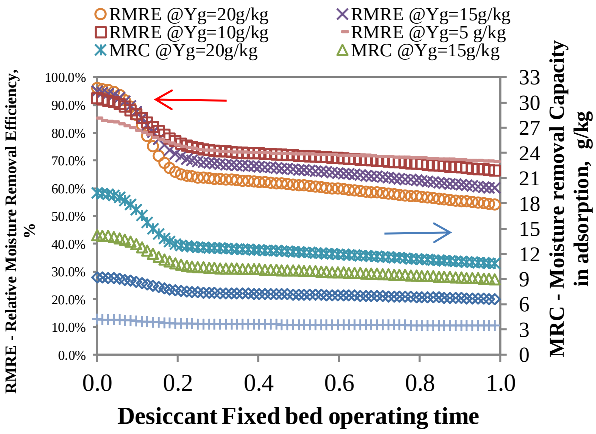

Fig. 5.Calculation of RMRE and MRC for different inlet moisture and temperature

Figure 6 shows the relative humidity in % for the bed sections across the length. It is seen that the moisture removal is very strong with the shorter length of bed, and the instantaneous relative humidity drop is very significant (that is from 100% at inlet, it is dried to 5.5% within 50% of the bed length).So in order to display the further drop of moisture contents, a logarithmic scale is used for Y-axis in all the RH graphs, a lowest value of 0.4% is able to be displayed clearly.

For the plots of DPT values achieved over the bed length, a conventional normal scale is used, as it can be seen in Figure 7. At the outlet a lowest DPT of about – 39.6°C using the hybrid bed #1 (50% : 50% = SG :MS) is shown in Figure 8 and Table 2, at the same time, the conventional MS bed gives a DPT of -39.01°C.

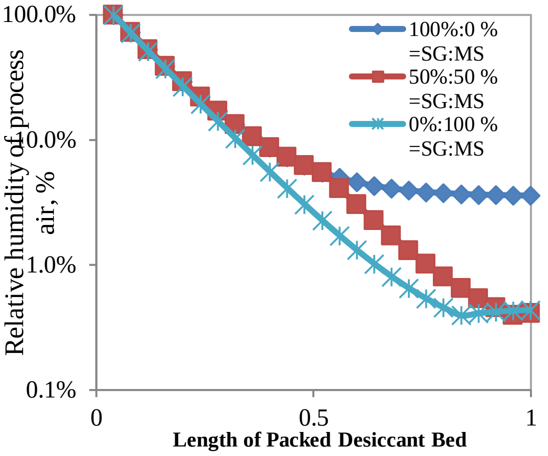

Fig. 6.Hybrid packed desiccant bed performance (RH) for 18 g/kg

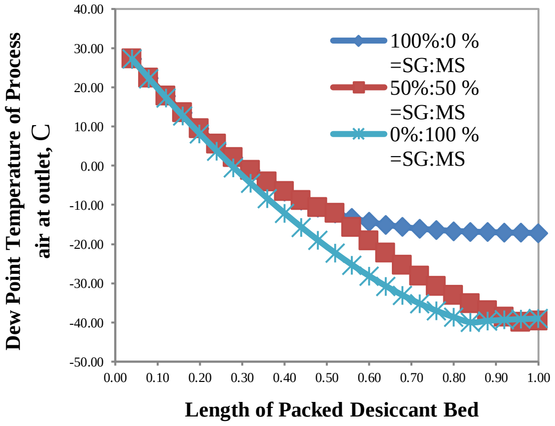

Fig. 7 Hybrid packed desiccant bed performance (DPT) for 18 g/kg

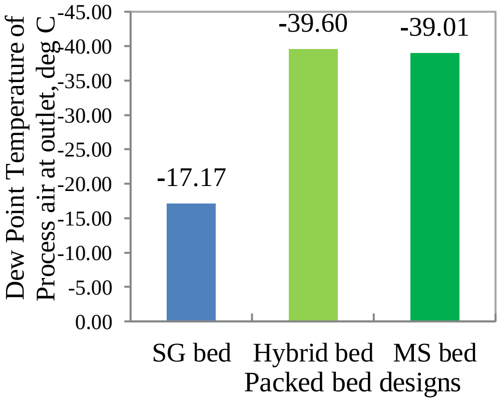

Fig 8 Performance of hybrid packed bed at 18 g/kg inlet

CONCLUSIONS

The numerical model shows a finer agreement with experimental data. The effect on output moisture content and temperature of air are predicted under the various input moisture contents.

The effect on output moisture content and DPT of air are predicted under different input moisture contents for the conventional SG, MS beds and hybrid bed.

The Hybrid bed with 50% of bed length with SG desiccant and remaining 50% of bed length with MS desiccant is superior to the conventional MS bed, by which the cost of hybrid bed can be lower than that of MS bed, without compromising the performance.

Table 2 DPT at outlet of the hybrid desiccant bed

Highest achieved Dew Point Temperature (°C)			
Inlet Moisture	SG bed	Hybrid bed	MS bed
18 g/kg	-17.17	-39.60	-39.01

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Definitions/Abbreviations

D_b	Diameter of the bed (m)
D_p	Diameter of the desiccant particle (m)
C_p	specific heat at constant pressure (kJ/kg K)
D_K	Knudsen diffusivity (m^2/s)
D_O	ordinary or molecular diffusivity (m^2/s)
D_S	surface diffusivity (m^2/s)
k	thermal conductivity (W/m K)
K_y	Convective Mass Transfer coefficient ($kg/m^2 s$)
h	convective heat transfer coefficient (kW/m^2K)
L	Length of the bed (m)
Le	Lewis number
Nu	Nusselt number
P	pressure (Pa)
Pa	Atmospheric pressure (Pa)
q_{st}	heat of adsorption J/kg desiccant
r	pore radius of the desiccant (m)
RH	Relative humidity (%)
Sh	Sherwood number
T	temperature (K)
t	Time
u	velocity (m/s)
W	adsorption in kg water vapour/kg desiccant
Y	Humidity ratio, kg water vapour/kg dry air
z	axial direction
Greek symbols	
ρ	density (kg/m^3)
ε	porosity
Subscripts	
0	initial state
a	air
d	desiccant
p	process air
r	Regeneration air
s	Solid desiccant

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